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# THE UNDERWATER ACOUSTIC SIGNATURE OF A NUCLEAR EXPLOSION AT THE OCEAN SURFACE

VELA SEISMOLOGICAL CENTER



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The gross spectral character and duration of the acoustic wave signature of a nuclear explosion near the ocean surface is estimated by constructing theoretical pressure-time histories, using models for the explosion and wave propagation. The explosion is assumed to have a yield of 1 KT and the nominal range is 6600 km. The frequencies of interest are rather low, 50 Hz and less, so absorption is small and the estimates of spectral character and duration

Cont'd

20. ABSTRACT (continued)

essentially decouple. The spectrum depends almost entirely on the source characteristics and the duration is controlled by characteristics of the travel path.

The airblast-induced pressure loading on the ocean surface dominates the source, with the acoustic waves from direct coupling into the water being relatively small. At large distances, the spectrum for 1 KT peaks near 20 Hz and is band-limited between 5 and 50 Hz. For different energy yields these frequencies scale with the cube-root of the yield. Different assumptions about the (laterally homogeneous) oceanic sound profile lead to differing estimates for the signal duration. Values of 20 to 60 seconds seem most reasonable.

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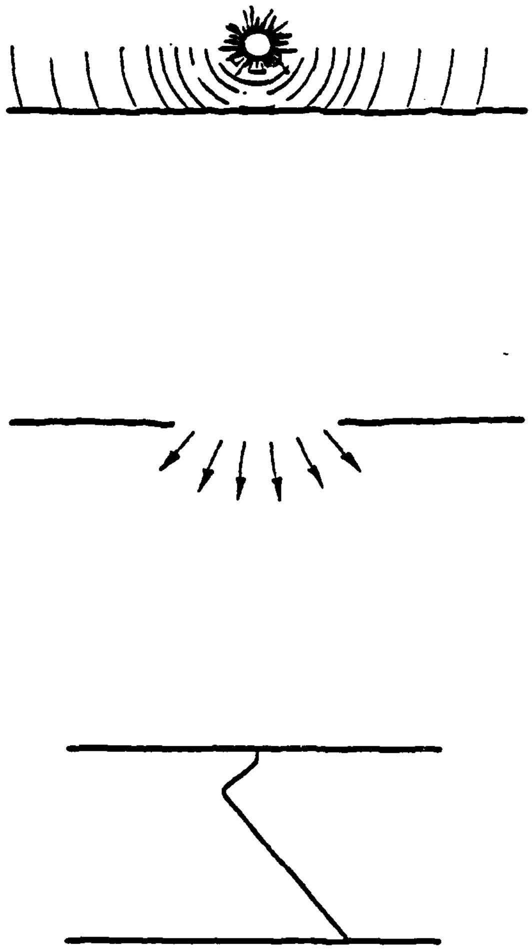
# I. INTRODUCTION

## 1.1 INTRODUCTION

Nuclear explosions detonated on or near the surface of the ocean are expected to excite acoustic waves that may be detected at large distances. In this report we attempt to estimate the gross spectral character and duration of the waves associated with such an event, assumed to have a yield of 1 KT.

To estimate the character of the acoustic signature of the explosion, we construct theoretical pressure-time histories, using models for the explosion and associated acoustic wave propagation. The assumptions of the model are outlined in some detail in Section II and are shown in schematic form in Figure 1. Basically, we convolve an elastic representation for the source with a Green's function representing the propagation. The source may include two parts. The first is the airblast loading applied to the surface and the second is the direct coupling of thermal energy into the water. When the explosion is assumed to be above a certain height, estimated to be about 2.3 meters for 1 KT, the direct coupling contribution is small. Thus, our calculations include the cases when the explosion is on or above the surface, though we have not attempted to account for burst height effects that may become important when the explosion is more than 10 meters above the surface. The spectra of both the airblast and direct coupled portions of the source are quite similar in character. They each are nearly flat at low frequency and have a corner frequency that occurs between 20 and 30 hertz.

For the propagation to ranges of 3000 kilometers and larger, we use a single sound velocity profile and a wave propagation technique adapted from seismology called WKBJ seismogram method (Chapmen, 1978, Brown, et al., 1980). The assumption of a



SOURCE:

AIRBLAST

Plus

DIRECT COUPLING FOR 1 KT
NEAR SURFACE EVENT

PROPAGATION:

WKBJ RAY THEORY IN A
LATERALLY HOMOGENEOUS
OCEAN

Figure 1. Schematic description of the construction of synthetic acoustic wave records. The source, represented by two pressure distributions applied to the ocean surface, is convolved with a Green's function representing the propagation.

laterally homogeneous ocean with a planar bottom is, of course, a rather idealized model for the actual situation.

At the frequencies of interest (< 50 Hz), absorption in the ocean is very small. Therefore, the spectral character of the source should be preserved at great distances. On the other hand, the duration of the acoustic signal is almost entirely dependent on characteristics of the travel path. Reasonable estimates for the path parameters suggest that the duration is between 20 and 60 seconds for a range of 6600 km.

We are not aware of empirical data describing the character of the acoustic signatures of nuclear explosions detonated over the deep ocean. However, we have seen sonograms made from hydrophone recordings of two French explosions detonated high above a Pacific atoll. The explosion yields were of the order of half a megaton and the burst heights were about 500 meters. The recordings were from a range of about 6000 km. The sonogram displays of the hydrophone recordings of these two events showed signals sharply limited in frequency and time. The time duration was about 13 seconds for one of the events and 8 seconds for the other, which had smaller yield. The spectra seemed to have a distinct corner frequency at 20 to 22 hertz.

We are not sure of the analog between the high yield, large height-of-burst atoll explosions and low yield near-surface explosions in the deep ocean, so relevance of the recordings of the French tests is unclear. Nevertheless, the characteristics we are attempting to bound for the prototype event are the signal duration and frequency content. We find that the acoustic signal at large distances from a 1 KT event should have a spectrum that peaks near 20 hertz. Nearly all the signal energy is between 5 and 50 hertz. The duration is estimated to be 20 to 60 seconds. These estimates do not seem too inconsistent with the data from the French tests.

# II. SYNTHETIC ACOUSTIC RECORDS

## 2.1 INTRODUCTION

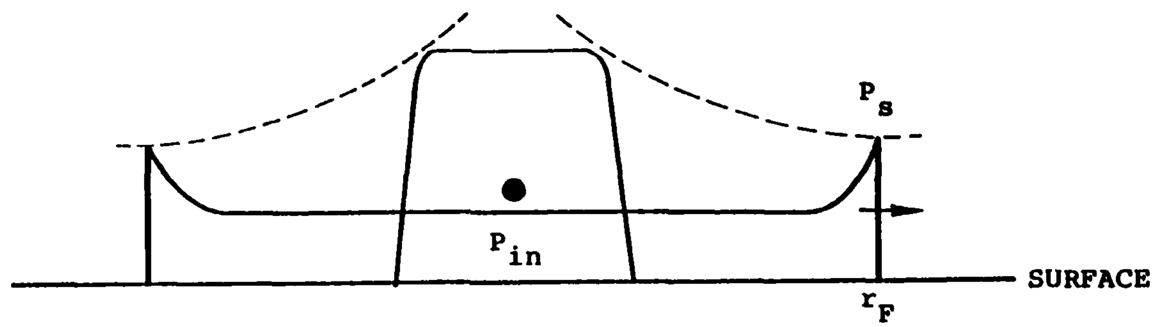
In this section we describe the assumptions of our analysis and summarize the results. Our conclusions are summarized in Section 2.8.

## 2.2 AIRBLAST SOURCE

The most important component of a near surface source is the airblast loading of the surface. This was represented by the Air Force Weapons Laboratory (AFWL) nuclear blast standard developed by Needham, et al. (1975). This model provides the pressure loading at the surface for a one-kiloton, free-air detonation at sea level. The pressure loading function is as indicated in Figure 2. Within a radius of 5 meters the peak pressure is 70 kbar. The peak then decays proportional to $r_F^3$ when $r_F > 5$ meters. After the shock front passes by, the pressure decays rapidly to $P_{in}$.

In applying the standard airblast load, large deformation of the water is ignored and acoustic wave theory is assumed to be valid. At each point on the surface a pressure, $P(r,t)$ calculated from subroutines given by Needham, et al. (1975), is applied and the resulting acoustic waves are computed, as will be subsequently described.

The standard airblast should be a good representation of the source for burst heights between 2.3 and 10 meters. The radius of the "burnout" sphere is about 2.3 meters for 1 KT, so below this height direct coupling of thermal energy into the water should be included. Above 10 meters there may be height-of-burst effects that should be accounted for in the $P(r,t)$.




$$P_s \sim 70 \text{ kbar}, \qquad r < 5 \text{ m}$$

$$P_s \sim \frac{1}{r_F^{\,3}} \qquad \frac{1}{r_F^{\,2}} \text{ for } r_F > 5 \text{ m}$$

$$P_{in} \sim \frac{1}{t^{1.15}}$$

Figure 2. Pressure loading for the airblast from a 1 KT near-surface explosion.

We do not know what might be the effect of ignoring the large "crater" that will be formed in the water by the near surface explosion. A far more detailed and expensive calculation would be required to estimate it.

## 2.3 DIRECT COUPLING

For near surface explosions, substantial amounts of energy may be directly coupled into the ocean. Details of this coupling will depend on the specific device design, but we can make some good estimates of the gross features. Numerous previous studies for the Defense Nuclear Agency (DNA) (e.g, Allen, et al., 1973; Allen and Baker, 1974) indicate that five to ten percent of the device energy is coupled to soil or water for a surface burst. Therefore, we completed a non-linear, hydrodynamic one-dimensional (plane strain) calculation of a 100 ton nuclear explosion in water. The calculation was continued into the linear response region, which was estimated to begin at a radius of 15 meters. A pressure pulse of the form shown in Figure 3 was then chosen as an "equivalent elastic source." This pressure pulse, when applied over 10 msec, gives the same total impulse as the detailed nonlinear calculation. The radius of 20 meters is the radius where the airblast loading dominates the direct coupling contribution predicted by this calculation. Note that this is not much different from the 15 meter elastic radius.

## 2.4 CALCULATION OF ACOUSTIC WAVES FROM AN EXPLOSION

The airblast and direct coupling portions of the source are both represented by pressure-time histories, P(r,t) applied to the ocean surface. Each point on the surface is then a source of acoustic waves and the total solution is obtained by convolving with the appropriate Green's functions.

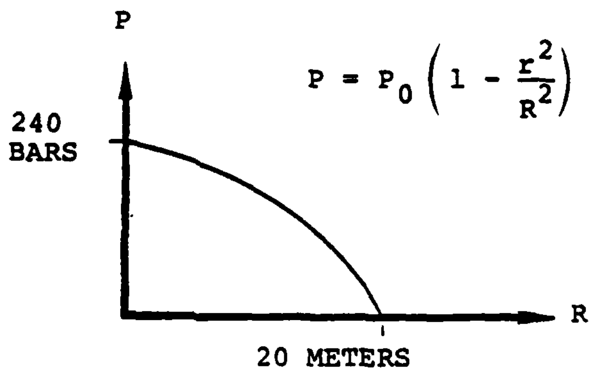



Figure 3. Spatial distribution of the pressure applied at the surface to represent the direct coupling of a 1 KT explosion into the water. This pressure is applied over 10 msec, which is effectively instantaneous for the time scale of this problem.

In this case, the Fourier transformed pressure at the receiver, $\hat{P}_r(\omega)$, is given by

$$\hat{P}_r(\omega) = i\omega\ \eta_R\ \hat{G}(\omega)\ \hat{F}(\omega) \quad , \tag{1}$$

where

$$\eta_R = \left(\frac{1}{c_R^2} - p^2\right)^{1/2} ,$$

$c_R$ is the sound velocity at the source and p is the ray parameter. The effective Green's function, $i\omega\eta_R G(\omega)$, is the spectral pressure at the receiver due to a vertical point load applied at the center of the source region. The $\hat{F}(\omega)$ is the total force applied by the source,

$$\hat{F}(\omega) = \int_0^b \hat{P}(r,\omega)\ J_0(\omega pr)\ rdr \quad , \tag{2}$$

where $\hat{P}(r,\omega)$ is the Fourier transform of the applied pressure, which is assumed to be negligible for $r > b$. All calculations were done with a single ray parameter ($p = 0.667$ sec/km). That is, we ignore small variations in $\hat{F}(\omega)$ for ray parameters (take-off angles) slightly different from this one. For each ray this formulation is valid for distances that are large compared to the source dimension, and for the time window of interest, all rays have essentially the same geometrical ray parameter.

In Figure 4 we plot the source spectra, $\hat{F}(\omega)$, associated with the airblast and direct coupling contributions. For an ocean path $\hat{G}(\omega)$ is expected to be a weak function of $\omega$ (though modulated by interference from many separate arrivals), and the pressure spectrum at the receiver should look roughly like $\omega$ times $\hat{F}(\omega)$.

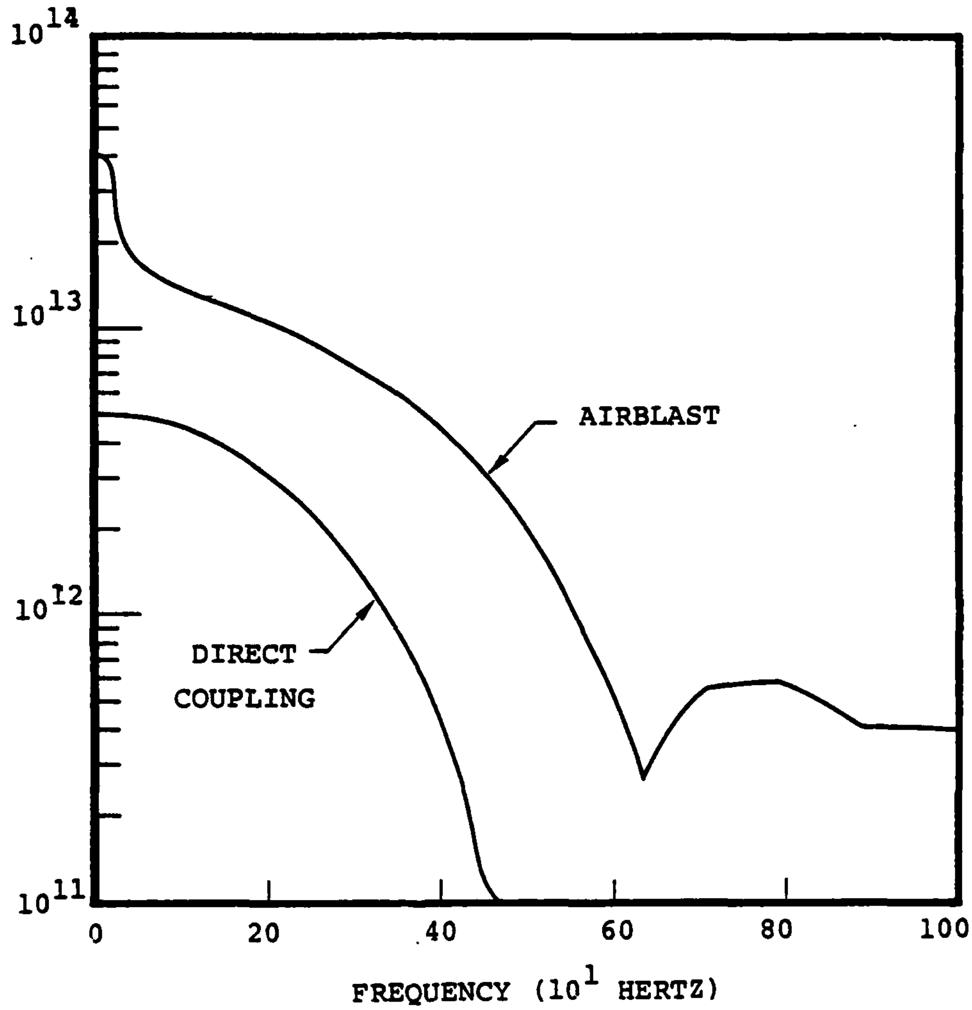



Figure 4. The explosion source spectra.

An important feature of the $\hat{F}(\omega)$ is that they both are low frequency sources that roll-off sharply above 25 or 30 Hertz. The airblast source is about three times as large as the direct coupling contribution. Thus, as far as acoustic waves are concerned, there is little to distinguish between sources on and above the surface.

The amplitude of the spectra in Figure 4 are controlled by the total impulse for each source component. In view of our simplifying assumptions, the relative values are certainly only rough estimates for the impulse amplitudes. However, they are probably correct in indicating that the airblast and direct coupling contributions are the same order, with the direct coupling contribution being somewhat smaller.

The corner frequencies in the $\hat{F}(\omega)$ are controlled by the source dimensions. Again, our calculations give rough estimates for this quantity, though errors of as much as a factor of two would be surprising.

### 2.5 THE GREEN'S FUNCTIONS — ACOUSTIC WAVES WITH WKBJ RAY THEORY

For the acoustic wave propagation in the ocean sound profile we used a method called WKBJ seismogram method. This method was developed by C. H. Chapman (1978) for computing synthetic seismograms in earth models. (A more accessible description of WKBJ ray theory is given by Aki and Richards, 1980, Section 9.4). M. J. Brown of Scripps Institute of Oceanography has adapted this theory for acoustic wave propagation in the ocean. Brown, et al., (1980) apply the technique to model 220 Hz acoustic wave propagation at a range of 900 kilometers in the northwest Atlantic. The results indicate that this technique gives some improvement over results from geometric ray theory.

Given the pressure, $P_r(\omega)$, at the receiver due to a concentrated pressure $P_o$ at the source, the Green's function is computed from

$$G(\omega) = \frac{\rho c(z)^2 P_r(\omega)}{P_o} \quad , \tag{3}$$

$\rho$ is the density at the receiver and $c(z)$ is the sound velocity which depends on the depth, z. The $P_r(\omega)$ is the Fourier transform of

$$P_r(t) = -\frac{1}{4\Pi^2(2r)^{1/2}} \operatorname{Im}\left\{\left|\frac{d}{dt}\right| \Lambda(t) * \sum_j \sum_{t=\theta_j} \frac{p^{1/2} R_j(p,z)}{|d\theta_j(p,r,z)/dp|}\right\} \tag{4}$$

where $R_j(p,z)$ is the product of reflection coefficients, which will be further described below, and

$$\Lambda(t) = \frac{H(t)}{t^{1/2}} + \frac{i\,H(-t)}{(-t)^{1/2}} \quad , \tag{5}$$

$$\theta_j(p,r,z) = pr + t_j(p,r,z) \quad . \tag{6}$$

In these equations, r is the range of the receiver. The travel time function is

$$t_j(p,z) = \int_{\text{raypath}} \left(\frac{1}{c(z)^2} - p^2\right)^{1/2} dz \quad . \tag{7}$$

The first sum in Equation (4) is over all j rays that reach the receiver. The second sum is over all p that satisfy $t = \theta_j(p,r,z)$.

Geometrical ray theory assumes a simple form for the contributions due to ray parameters near the geometrical ray parameter in equation (4), and replaces the second sum with a simple time function. The WKBJ seismogram includes these contributions more rigorously. It is usually considered to be an excellent approximation for periods much less than the total travel time.

The $R_j(p,z)$ is given by

$$R_j(p,z) = \left[\left(\frac{1}{c(z_o)^2} - p^2\right)\left(\frac{1}{c(z)^2} - p^2\right)\right]^{-1/4} \prod_{k=1,m} R_k \qquad (8)$$

where $\prod_{k=1,m} R_k$ is the product of the reflection coefficients along the ray. These are -i for each turn within the ocean, -1 for a reflection at the surface and $\xi < 1$ for each reflection at the ocean bottom.

The types of rays included in the WKBJ theory are indicated schematically in Figure 5. The parameter $\xi$ accounts for leakage of energy into the bottom sediments on each bottom reflection. Estimates for this bottom loss are available in the literature, though at frequencies somewhat higher than those of interest here. Using a plot in Section 5.8 of Urick (1975) we estimated that 0.977 should be on upper bound for $\xi$.

Absorption in the water is very small at the frequencies (< 50 Hz) of interest. It was ignored. Also ignored is any loss from reflection at the surface.

Shown at the right in Figure 5 is a typical sound velocity profile. Indicated on this profile is the point at depth which has the same velocity as the velocity at the

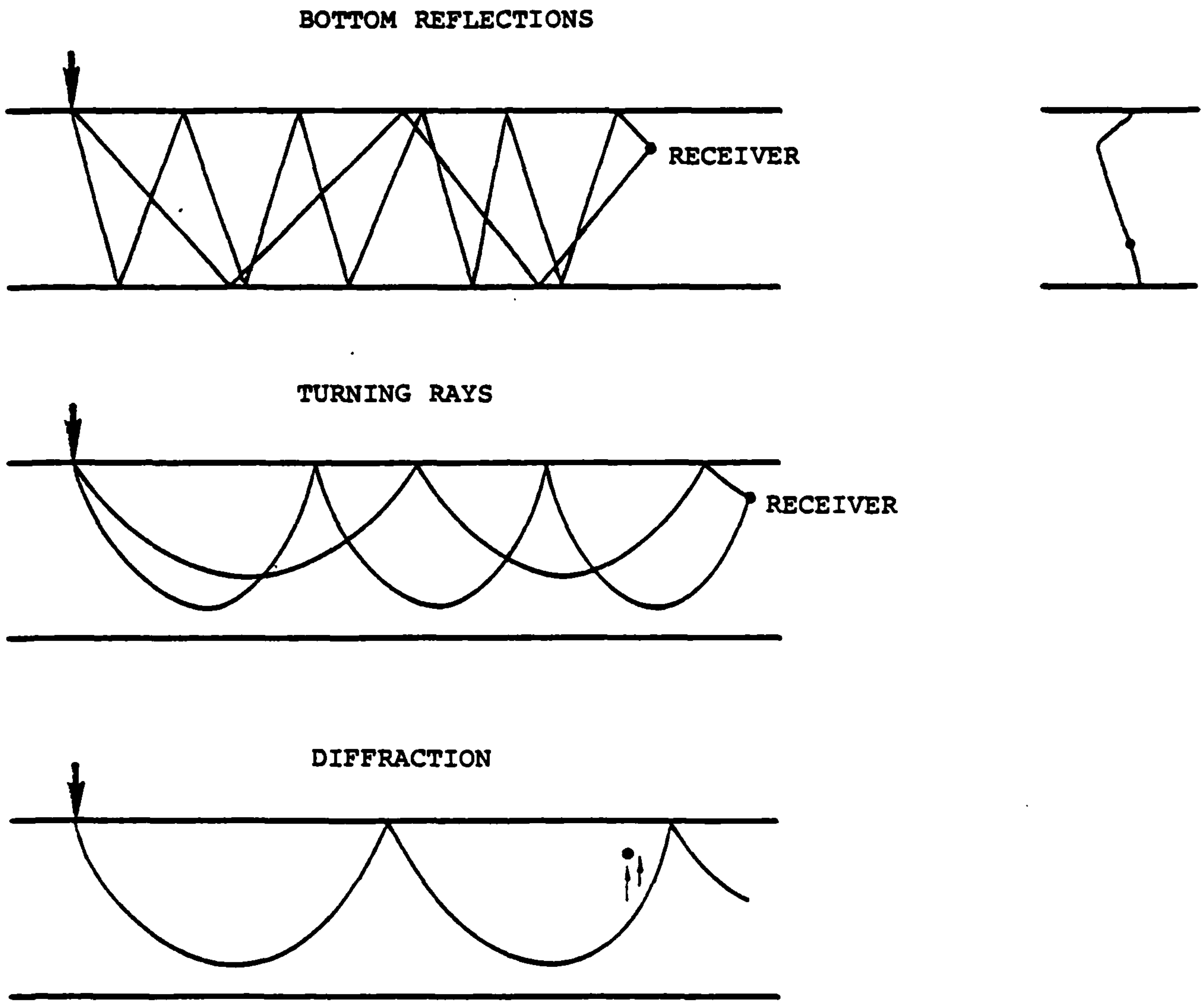



Figure 5. Rays included in the WKBJ ray solution. A typical sound velocity profile is shown at the right. The dot indicates the point at which the velocity is the same as at the surface.

surface. All rays must turn below this depth. As currently implemented, this theory is unable to account for waves trapped in the region where velocities are lower than at the surface; that is, SOFAR channel waves.

The most serious limitation of the theory is that it fails to account for scattering due to lateral changes in the ocean bottom and in the sound velocity profile. Such scattering would introduce energy into the low velocity channel, where it would be trapped and travel quite efficiently. The theory is being modified to account for such phenomena.

In summary, Equation (1) indicates that the acoustic wave signature of the event is obtained from the derivative of the convolution of the source function (Figure 4) with the Green's function, $\hat{G}(\omega)$, would be essentially constant over the frequency band, though with some scalloping due to interference between arrivals, then

$$\hat{P}_r(\omega) \approx i\, \omega\, \hat{F}(\omega) \tag{9}$$

gives a smoothed estimate for the spectrum at the receiver.

The WKBJ theory is a finite wavelength theory that gives higher order corrections to geometric ray theory. However, numerical tests indicate that the only gross differences between $G(\omega)$ computed with our WKBJ seismogram program and that expected from geometric ray theory were due to the low frequency band width, which is determined by discretization of the time series and the smoothing required to prevent aliasing. Thus, as far as the important characteristics of the answers are concerned, we may as well have used geometric ray theory.

Our final estimates for the acoustic waves from the near surface explosion were made in the following way. The <u>spectrum</u> was computed from Equation (9). That is, the travel path plays no role in filtering the spectrum, other than

through the differentiation that comes from the force-pressure relationship. This is the result we would get with geometric ray theory. The duration of the recorded signal is estimated by the WKBJ ray theory program. However, as we will describe in Section 2.7, we will make some crude adjustments to these estimates in an attempt to account for scattering effects not present in the model.

## 2.6. THE SPECTRAL SIGNATURE AT THE RECEIVER

As we explained in the previous section, for frequencies less than 60 Hz or so, the oceanic acoustic waves are propagated with little frequency distortion. Thus, (9) gives an estimate for the (smoothed) spectrum of the signal recorded at large distances from a nuclear explosion on or near the ocean surface. That is, we simply multiply the spectra in Figure 4 by $i\omega$.

In Figure 6 we plot our estimates for the spectra of the pressure pulse at a hydrophone station. The plots with and without the direct coupling contribution are shown. As expected, it makes little difference.

The other important characteristic of the spectra in Figure 6 is that they are band limited, having a peak near 22 Hz and being down a factor of 3 from this peak at about 4 and 50 Hz.

One factor we have not included in these calculations is the hydrophone response. At low frequencies, the response is roughly proportional to $\omega$ (LTC T. Jerrick, AFTAC, personal communication), which makes the spectrum fall-off even more sharply on this side. The hydrophone response on the high frequency side of the peak is not known to us.

We should also point out that the spectra cube-root scale with yield. That is, if the yield were twice the 1 KT

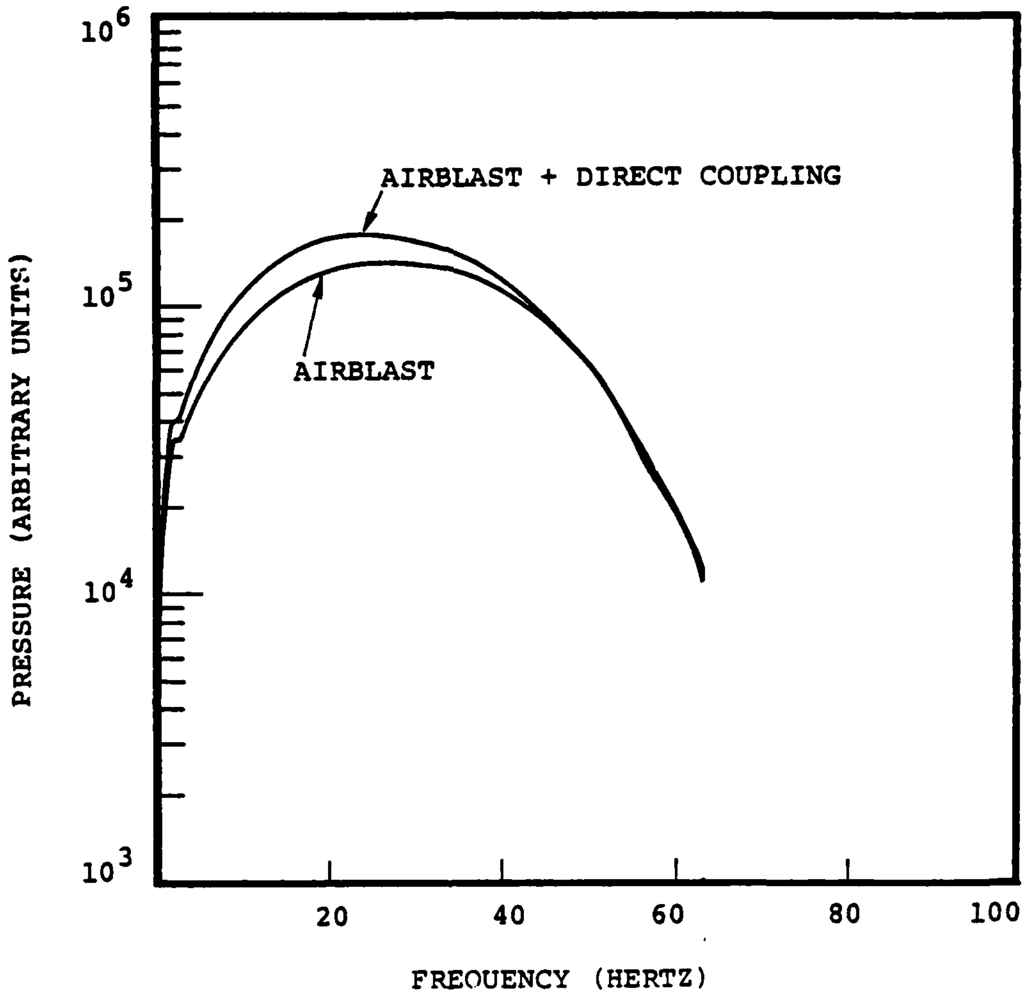



Figure 6. The spectrum of the pressure time history of a single ray arrival at a SOFAR axis receiver station. The complete signal spectrum, which is a sum of many single ray spectra, would have the same basic shape. The amplitude units are arbitrary, depending on the amplitude of the Green's function for the travel path.

value assumed, the spectral peak would move from 22 Hz to 17.5 Hz and the region with amplitudes within 33 percent of the peak moves from 4 - 50 Hertz to 3 - 40 Hertz.

## 2.7 ESTIMATES OF SIGNAL DURATION

To estimate the signal duration, we computed the Green's functions for several typical oceanic profiles. The Green's function is the pressure at the receiver due to a concentrated force on the surface at the source. This was computed using the WKBJ seismogram technique described in the previous section.

The ocean profiles were taken from compilations of sound velocity data for the south Atlantic Ocean. Four profiles were chosen that represent extremes during the early Fall in this part of the ocean. These profiles are shown in Figure 7.

The Green's functions were computed at ranges from 3600 to 6600 kilometers. At 6600 km a typical calculation includes rays with 90 to 140 turning points. There are a similar number of bottom bounces. As mentioned before, we assumed the reflection coefficient at the bottom to be $\xi$ = 0.977. Then for 100 bounces the total attenuation is 0.01. Therefore, the bottom bounces make almost no contribution to the record at such large ranges.

In Figure 8 we plot the Green's functions at 6600 kilometers for the four profiles in Figure 6, with the bottom depth assumed to be 5000 meters. The records are dominated by the delta function contributions from the turning rays.

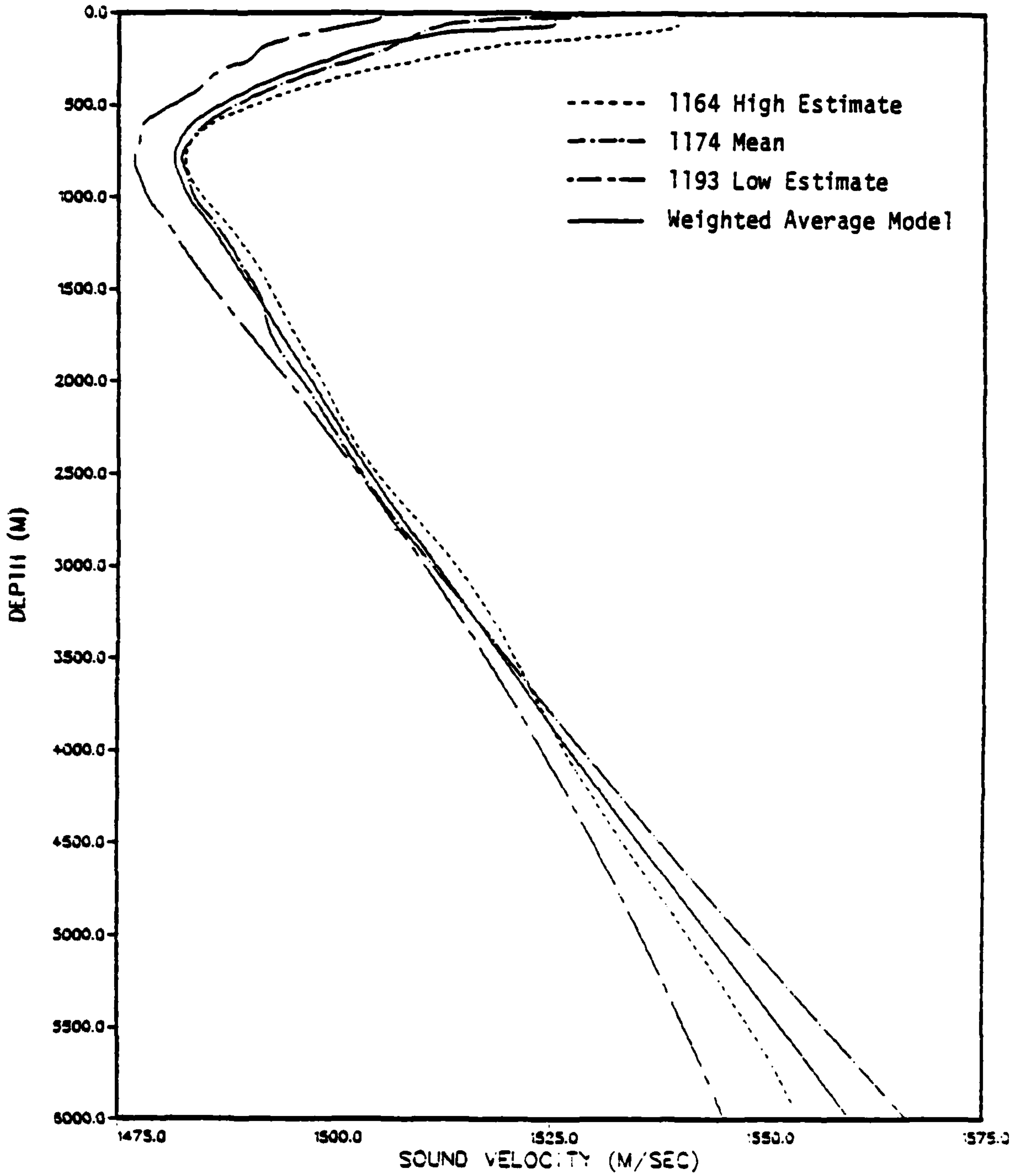



Figure 7. Sound velocity profiles.

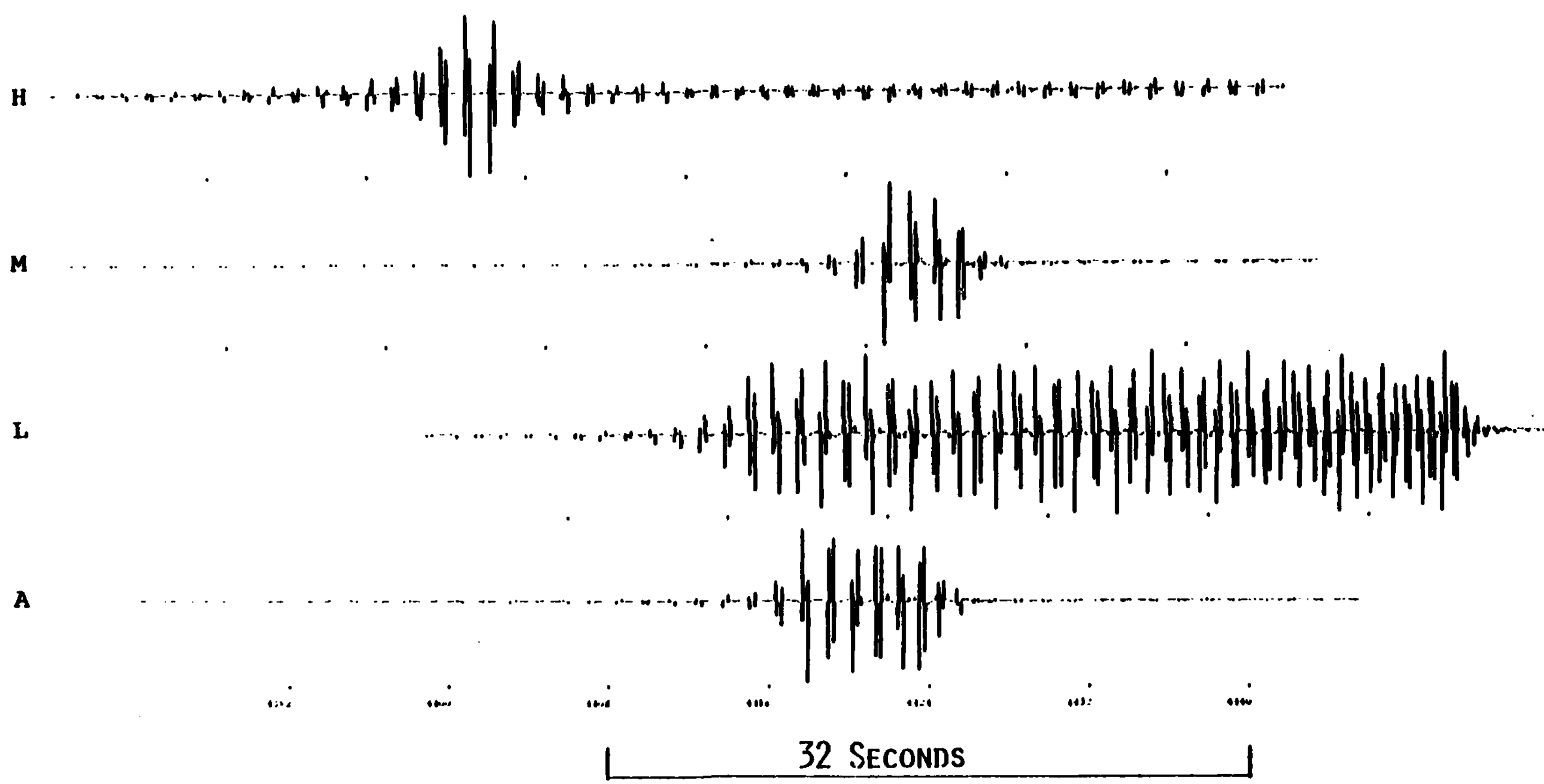



Figure 8. The Green's functions for the velocity profiles of Figure 7.

The bottom bounces arriving earlier and later are much smaller. There are also some diffraction effects, but they are quite small.

The duration of the Green's functions was estimated from the window within which the amplitudes are 30 percent of the maximum and greater. The measurements were done by eye, with no attempt to be precise. For example, the duration for the "average" model in Figure 8 was taken to be 9 seconds.

Similar calculations were done for several parameter variations. In particular, we varied the following:

1. Range - The duration was found to be directly proportional to the range, as should be expected. The Green's functions are shown in Figure 9.

2. Bottom Depth - Shallower depths give a smaller window for the turning rays (Figure 5). Therefore, there are fewer such rays and a shorter duration. Deeper depths give a larger window and commensurately larger duration. Several Green's functions illustrating this are given in Figure 10.

3. Surface Velocity - The velocity near the surface is probably quite variable along the path. This velocity was decreased slightly (from 1525 to 1520 m/sec in the top 10 meters) in the "average" path model (A). The resulting model is called "A MOD." The main effect is again to increase the depth window for turning rays and thus to increase the duration. Some examples are shown in Figure 10.

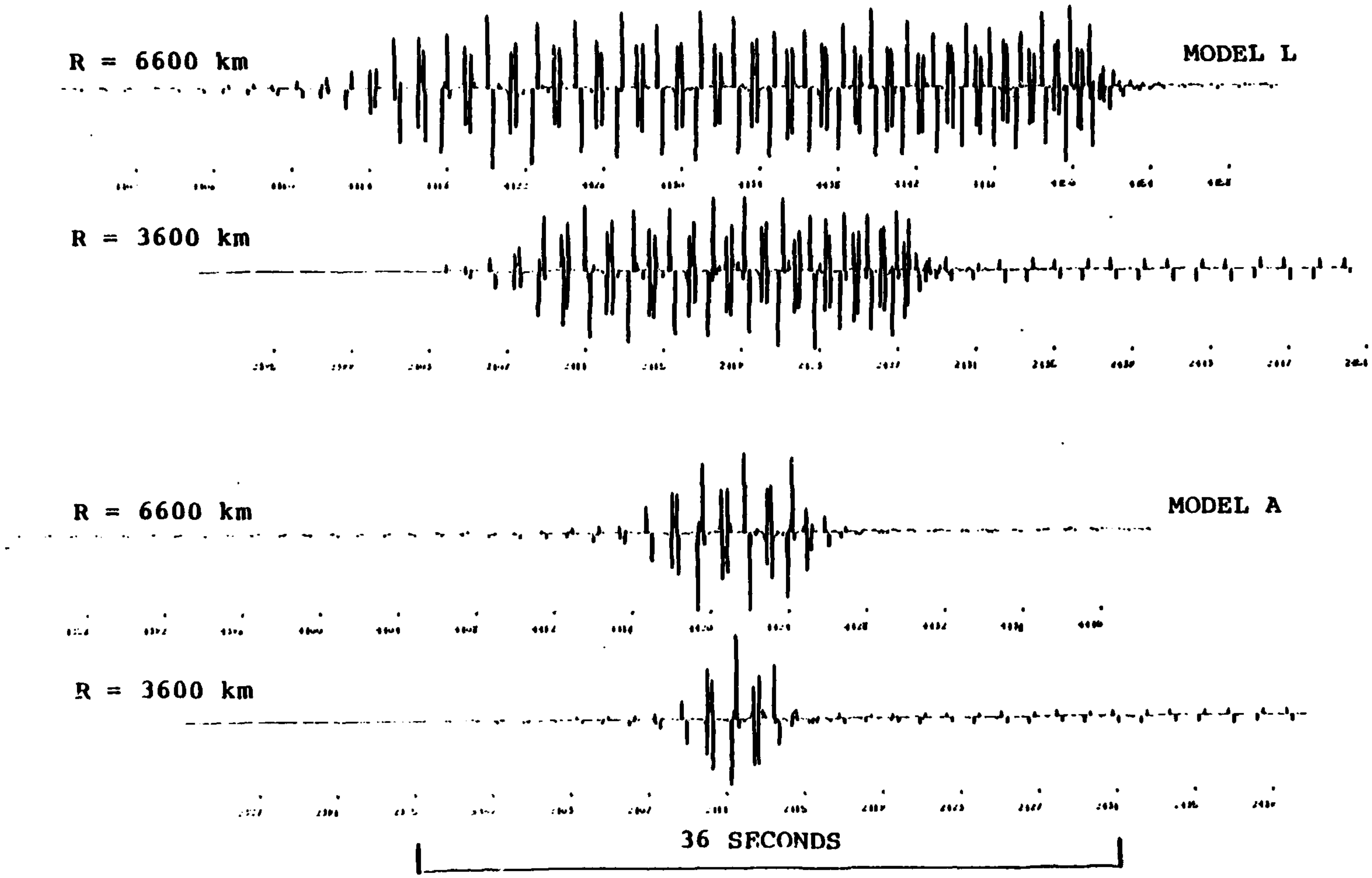



Figure 9. The dependence of the Green's functions on range for two models.

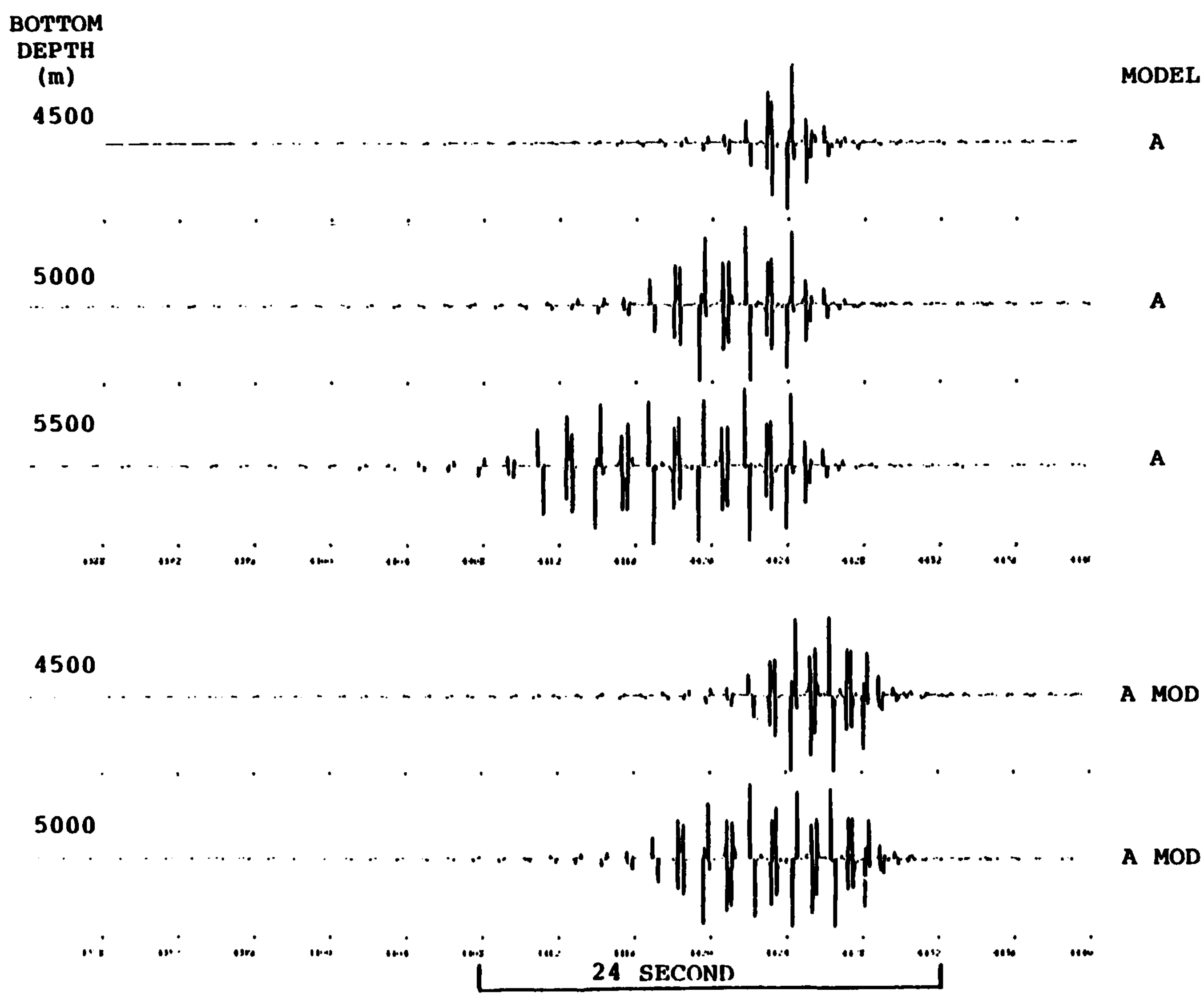



Figure 10. Green's function variations for different bottom depths and near surface velocities.

As we have mentioned, the failure to account for energy that is scattered into the SOFAR channel is the main weakness of the theory. The onset time is probably reasonably accurate, if the profile represents a good average for the entire path. As a crude estimate for the extended duration due to late arriving energy which propagates in the SOFAR channel, we computed $R/c_o$, the arrival time for a wave at the axis. An "extended duration" was then taken to be the time between the onset time, measured on the Green's function plots, and $R/c_o$.

In Table 1 we summarize our duration estimates. If we use the results directly from the model, the duration varies from 4 to 38 seconds. Extending the duration by assuming arrivals at the SOFAR axis velocity, the duration estimates are less variable, ranging from 22 to 55 seconds. The latter estimates are much more realistic.

## 2.8 CONCLUSIONS

Our main conclusions about the acoustic waves at large ranges from a 1 KT near-surface explosion are as follows:

- For the low frequency (< 50 Hertz) signals of interest, estimates for the spectral content and duration may be decoupled. The former is almost entirely controlled by the source and the latter by the sound velocity profile along the travel path.
- The direct coupling of energy into the water seems relatively unimportant compared to the airblast loading.
- The acoustic signal spectrum is peaked at about 22 Hertz and falls off to values one-third the peak at about 4 and 50 Hertz. This spectrum cube-root scales with yield. That

TABLE 1

SUMMARY OF DURATION ESTIMATES

| Model | Bottom Depth D(km) | Range R(km) | Duration (sec) | SOFAR Axis Velocity | Extended Duration |
|---|---|---|---|---|---|
| H | 5.0 | 6600 | 12 | 1482.7 | 55 |
| M | 5.0 | 6600 | 7 | 1482.28 | 32 |
| L | 5.0 | 6600 | 38 | 1476.79 | 55 |
| A | 5.0 | 6600 | 9 | 1481.39 | 38 |
| A | 4.5 | 6600 | 4 | 1481.39 | 33 |
| A | 5.5 | 6600 | 16 | 1481.39 | 45 |
| A Mod | 4.5 | 6600 | 7 | 1481.39 | 38 |
| A Mod | 5.0 | 6600 | 12 | 1481.39 | 33 |
| L | 5.0 | 3600 | 22 | 1476.79 | 31 |
| A | 5.0 | 3600 | 6 | 1481.39 | 22 |

is, at 2 KT the characteristic frequencies are a factor of 1.26 smaller. The spectral estimates do not account for the recording system response.

- The duration of the acoustic signal varies widely, depending on the assumptions about the travel path. Values from 20 to 60 seconds seem reasonable for a range of about 6600 kilometers.

These conclusions are based on an analysis that includes many approximations. It is useful to list these here. They are:

- The explosion is represented by the AFWL 1 KT nuclear blast standard. The near-surface 1 KT airblast is assumed to be the same as the airblast from 2 KT in free air.
- The airblast loading is applied as a pressure to the surface of the ocean, which deforms elastically.
- The direct coupling is accounted for by an equivalent pressure source which is estimated via the process described in Section 2.3.
- For energy travelling along paths entirely within the ocean, the absorption is negligible at the low frequencies of interest.
- The travel path is represented by a single sound-velocity profile. Several such paths are used.
- The last assumption implicitly assumes that the explosion is detonated over deep ocean.
- The recording system response is not included in our spectral estimates.

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